CARDIAC RHYTHM MANAGEMENT SYSTEM SELECTING A-V DELAY BASED ON INTERVAL BETWEEN ATRIAL DEPOLARIZATION AND MITRAL VALVE CLOSURE

Cross-Reference to Related Application(s)

This application is a division of U.S. Patent Application No. 09/862,763, filed on May 21, 2001, the specification of which is incorporated herein by reference.

Technical Field

The present system relates generally to cardiac rhythm management systems and particularly, but not by way of limitation, to such a system selecting A-V delay based on interval between an atrial depolarization and a mitral valve closure.

Background

When functioning properly, the human heart maintains its own intrinsic rhythm, and is capable of pumping adequate blood throughout the body's circulatory system. However, some people have irregular cardiac rhythms, referred to as cardiac arrhythmias. Such arrhythmias result in diminished blood circulation. One mode of treating cardiac arrhythmias uses drug therapy. Drugs are often effective at restoring normal heart rhythms. However, drug therapy is not always effective for treating arrhythmias of certain patients. For such patients, an alternative mode of treatment is needed. One such alternative mode of treatment includes the use of a cardiac rhythm management system. Such systems are often implanted in the patient and deliver therapy to the heart.

Cardiac rhythm management systems include, among other things, pacemakers, also referred to as pacers. Pacers deliver timed sequences of low energy electrical stimuli, called pace pulses, to the heart, such as via an intravascular leadwire or catheter (referred to as a "lead") having one or more electrodes disposed

in or about the heart. Heart contractions are initiated in response to such pace pulses (this is referred to as "capturing" the heart). By properly timing the delivery of pace pulses, the heart can be induced to contract in proper rhythm, greatly improving its efficiency as a pump. Pacers are often used to treat patients with bradyarrhythmias, that is, hearts that beat too slowly, or irregularly. Some pacers coordinate atrial and ventricular contractions to improve pumping efficiency. Cardiac rhythm management systems also include coordination devices for coordinating the contractions of both the right and left sides of the heart for improved pumping efficiency.

Cardiac rhythm management systems also include defibrillators that are capable of delivering higher energy electrical stimuli to the heart. Such defibrillators also include cardioverters, which synchronize the delivery of such stimuli to sensed intrinsic heart depolarizations. Defibrillators are often used to treat patients with tachyarrhythmias, that is, hearts that beat too quickly. Such too-fast heart rhythms also cause diminished blood circulation because the heart isn't allowed sufficient time to fill with blood before contracting to expel the blood. Such pumping by the heart is inefficient. A defibrillator is capable of delivering a high energy electrical stimulus that is sometimes referred to as a defibrillation countershock, also referred to simply as a "shock." The countershock interrupts the tachyarrhythmia, allowing the heart to reestablish a normal rhythm for the efficient pumping of blood. In addition to pacers, cardiac rhythm management systems also include, among other things, pacer/defibrillators that combine the functions of pacers and defibrillators, drug delivery devices, and any other implantable or external systems or devices for diagnosing or treating cardiac arrhythmias.

One problem faced by cardiac rhythm management systems is the proper timing relationship between a sensed or paced atrial depolarization and the subsequent delivery during the same cardiac cycle of a ventricular pacing pulse. This atrioventricular time interval is referred to as the A-V delay. The A-V delay provided by a cardiac rhythm management system may be programmed by the

physician to tailor the therapy for a particular patient. The actual value of the A-V delay affects the blood flow from the atrium to the ventricle and, therefore, affects the cardiac output of the heart. The blood flow from the atrium to the ventricle has two components. After the ventricle has completed a contraction, it begins to relax, with blood entering the ventricle from the corresponding atrium when the atrial pressure exceeds the ventricular pressure. This pulse-like fluid flow is sometimes referred to as the "E-wave" of a Doppler echocardiograph. Next, the atrium contracts to actively expel a second pulse-like flow of fluid, sometimes referred to as the Doppler echocardiographic "A-wave," to the ventricle. For a given fixed time interval between ventricular contractions, if the A-V delay is set too long, then the atrial contraction is moved closer to the preceding ventricular contraction. Because the A-wave and the E-wave occur closer together in time, there is a reduction in total ventricular filling time. By contrast, if the A-V delay is set too short, then the ventricle does not receive the full benefit of the blood flow during the A-wave. For these and other reasons, there is a need to select an A-V delay value that promotes increased blood flow from the atrium to the ventricle, thereby increasing cardiac output.

Summary

This document discusses a cardiac rhythm management system that, among other things, selects an A-V delay based on an interval between an atrial depolarization and a mitral valve closure.

In one embodiment, the system includes a method in which ventricular stimulations are provided. The ventricular stimulations are separated from corresponding preceding atrial depolarizations, occurring during the same cardiac cycle, by different atrioventricular (A-V) delays. The system detects mitral valve closures associated with each pair of atrial and ventricular stimulations. The system measures P-MVC time intervals between the atrial depolarizations and the mitral valve closures. In one embodiment, the slopes of the P-MVC time intervals are

calculated against the different A-V delays. Based on the slopes, an A-V delay is selected for subsequent delivery of ventricular stimulations. In an alternate embodiment, linear approximations of the P-MVC time intervals (as a function of the different A-V delays) are used for selecting the A-V delay.

Brief Description of the Drawings

In the drawings, which are not necessarily drawn to scale, like numerals describe substantially similar components throughout the several views. Like numerals having different letter suffixes represent different instances of substantially similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

Figure **1** is a schematic/block diagram illustrating generally, among other things, one embodiment of portions of a cardiac rhythm management system and an environment in which it is used.

Figure **2** is a schematic/block diagram illustrating generally one embodiment of portions of a mitral valve closure fiducial point generator.

Figure **3** is a graph illustrating an example of different P-MVC time intervals, between atrial depolarizations and corresponding subsequent mitral valve closures, obtained in response to different test A-V delays.

Figure **4** is a graph illustrating generally a technique for selecting an A-V delay based on an intersection between a first linear approximation of P-MVC time intervals at short A-V delays and a second linear approximation of P-MVC time intervals at longer A-V delays.

Figure **5** is a flow chart illustrating generally one embodiment of an example technique for selecting an appropriate A-V delay at which to deliver subsequent ventricular stimulation therapy.

Figure **6** is a schematic/block diagram illustrating generally, among other things, one embodiment of portions of a cardiac rhythm management system including an electrode associated with the left side of the heart, and an environment

in which it is used.

Detailed Description

In the following detailed description, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that the embodiments may be combined, or that other embodiments may be utilized and that structural, logical and electrical changes may be made without departing from the spirit and scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined by the appended claims and their equivalents. In the drawings, like numerals describe substantially similar components throughout the several views. Like numerals having different letter suffixes represent different instances of substantially similar components. The term "and/or" refers to a nonexclusive "or" (i.e., "A and/or B" includes both "A and B" as well as "A or B").

This document discusses a cardiac rhythm management system that, among other things, selects an A-V delay based on an interval between an atrial depolarization and a mitral valve closure. The present methods and apparatus will be described in applications involving implantable medical devices including, but not limited to, implantable cardiac rhythm management systems such as pacemakers, cardioverter/defibrillators, pacer/defibrillators, biventricular or other multi-site coordination devices, and drug delivery systems. However, it is understood that the present methods and apparatus may be employed in unimplanted devices, including, but not limited to, external pacemakers, cardioverter/defibrillators, pacer/defibrillators, biventricular or other multi-site coordination devices, monitors, programmers and recorders, whether such devices are used for providing a diagnostic, a therapy, or both a diagnostic and a therapy.

Figure **1** is a schematic/block diagram illustrating generally one embodiment of portions of the present cardiac rhythm management system **100** and an environment in which it is used. In this embodiment, system **100** includes, among other things, cardiac rhythm management device **105**, which is coupled by leads **110A-B** to heart **115**. Heart **115** includes four chambers: right atrium **115A**, right ventricle **115B**, left atrium **115C**, and left ventricle **115D**.

In one embodiment, lead **110A** includes an electrode associated with right atrium **115A**, such as tip electrode **120** and/or ring electrode **125**. The electrode is "associated" with the particular heart chamber by inserting it into that heart chamber, or by inserting it into a portion of the heart's vasculature that is close to that heart chamber, or by epicardially placing the electrode outside that heart chamber, or by any other technique of configuring and situating an electrode for sensing signals and/or providing therapy with respect to that heart chamber. Lead **110B**, which in one embodiment is introduced into right ventricle **115B**, includes an electrode associated with right ventricle **115B**, such as electrodes **130** and **135**. Device **105** may also include other electrodes, such as housing electrode **140** and/or header electrode **145**, which are also associated with heart **115**, and which are useful for, among other things, "unipolar" sensing of heart signals or unipolar delivery of contraction-evoking stimulations in conjunction with one or more of the electrodes **120**, **125**, **130**, and **135** associated with heart **115**. Alternatively, "bipolar" sensing and/or therapy may be used between electrodes **120** and **125**, and between each of electrodes **130** and **135** and another closely situated electrode (not shown).

In one embodiment, device **105** includes an atrial sensing module **150** and a ventricular sensing module **155**, which are each coupled to one or more of the electrodes, such as electrodes **120** and **130**, respectively, for sensing intrinsic and/or evoked electrical depolarizations corresponding to heart chamber contractions. Such electrical depolarizations of the heart tissue include atrial depolarizations, referred to as P-waves, and ventricular depolarizations, referred to as QRS complexes. The QRS complex is a rapid sequence of three signal excursions away

from a baseline in sequentially switching polarity, with the first excursion referred to as a Q-wave, the second (typically the largest) excursion referred to as an R-wave, and the third excursion referred to as the S-wave. Device **105** also includes atrial stimulation module **160** and ventricular stimulation module **165**, respectively coupled, in this example, to atrial electrode **120** and ventricular electrode **130** for providing stimulation energy pulses thereto. Such stimulation energy pulses typically evoke heart contractions of the heart chambers with which their respective electrodes are associated.

Device **105** also includes a mitral valve closure detector that, in one embodiment, includes accelerometer **170**. In one embodiment, accelerometer **170** is carried within the housing of device **105**, which is pectorally or abdominally implanted in close enough proximity to heart **115** to sense acceleration from heart **115**. Accelerometer **170** outputs a heart acceleration signal to analog-to-digital (A/D) converter **175**, for conversion into a digitized signal along with the atrial heart signal output by atrial sensing module **150** and the ventricular heart signal output by ventricular sensing module **155**. A/D converter is coupled to controller **180** for providing these digital signals to controller **180**.

Controller **180** includes hardware components and/or microcontroller or microcontroller-like executable operations that implement an accelerometer interface such as mitral valve closure (MVC) fiducial point generator **182**, a timer **184**, a memory **186**, a slope calculation module **188**, and an atrioventricular (A-V) delay selection module **190**. MVC fiducial point generator **182** is coupled to accelerometer **170** through A/D converter **175** such that it receives a digitized heart acceleration signal. Based upon this digitized heart acceleration signal, MVC fiducial point generator **182** detects mitral valve closures of heart **115** and provides MVC fiducial points associated with the occurrence of such mitral valve closures.

Timer **184** is coupled to atrial stimulation circuit **160** and/or ventricular stimulation circuit **165** for delivering timing signals that control the delivery of the atrial and/or ventricular stimulation pulses. In an embodiment employing atrial

sensing and/or pacing as well as ventricular pacing and/or sensing, these timing signals determine the A-V delay time interval between successive atrial and ventricular senses/stimulations occurring during the same cardiac cycle. Timer **184** also measures the time interval, referred to as a P-MVC time interval, between an atrial contraction (measured either from the issuance of an atrial stimulation pulse or, alternatively, from the detection of a sensed intrinsic or evoked atrial contraction) and a next MVC fiducial point detected by accelerometer **170**.

Timer **184** measures the P-MVC time intervals over several cardiac cycles for which the A-V delay between delivered or sensed atrial and ventricular contractions is varied over a range of values such as, by way of example, but not by way of limitation, approximately between 10 milliseconds and 250 milliseconds, inclusive, at increments that are approximately between 10 milliseconds and 50 milliseconds, inclusive. The measured P-MVC time intervals and corresponding A-V delay values are stored in memory locations in memory **186**. Based on this data, slope calculation module **188** calculates the slope of the P-MVC time intervals against corresponding adjacent A-V delay values, by taking a difference between adjacent P-MVC time intervals divided by a difference between corresponding adjacent A-V delay values. The resulting calculated slopes are stored in memory locations in memory **186**. Based on these calculated slopes, A-V delay selection module **190** determines an appropriate A-V delay for use in subsequent delivery of ventricular stimulations to heart **115** in conjunction with either intrinsic or paced atrial heart depolarizations. In a further embodiment, an indication of the appropriate A-V delay as determined by A-V delay selection module **190** is provided to transceiver **192**, which is coupled to controller **180**, and transmitted to external interface **194** for display to a physician or other user, such as on a computer monitor, printout, or other data output mechanism.

Figure **2** is a schematic/block diagram illustrating generally one embodiment of portions of MVC fiducial point generator **182**, including a highpass filter **200**, a lowpass filter **202**, a highpass filter **205**, and a peak detector **210**, although it is

understood that certain of these components could be combined rather than implemented separately (e.g., a highpass and lowpass filter could be combined into a bandpass filter, etc.). In one embodiment, highpass filter **200** receives the digitized heart acceleration signal from A/D converter **175**, removes baseline (i.e., constant or low frequency drift) signal components, and provides a resulting output signal to an input of lowpass filter **202**. In this example, lowpass filter **202** is a 5-sample moving average "boxcar" filter attenuating signal frequencies above approximately 100 Hz. Lowpass filter **202** receives the baseline-filtered heart acceleration signal from highpass filter **200**, and outputs a resulting lowpass filtered heart acceleration signal to an input of highpass filter **205**. In one embodiment, highpass filter **205** is a differentiator that takes a first derivative of its input lowpass filtered heart acceleration signal received from the output of lowpass filter **202** and outputs a resulting first derivative heart acceleration signal to an input of peak detector **210**. In one embodiment, peak detector **210** detects negative peaks of the first derivative heart acceleration signal. However, it is understood that a polarity reversal of accelerometer **170** and/or signal inversion(s) in the signal processing path of the heart acceleration signal may alternatively require a detection of positive peaks of the first derivative heart acceleration signal. For each cardiac cycle, the first negative peak of the first derivative heart acceleration signal occurring after the delivery of a ventricular stimulation and before the next intrinsic or paced atrial depolarization is deemed an MVC fiducial point associated with the mitral valve closure. An indication of the time at which such MVC fiducial points occur is provided by MVC fiducial point generator **182** to timer **184** for calculation of the corresponding P-MVC time intervals discussed above.

Figure **3** is a graph illustrating an example of the different P-MVC time intervals obtained by timer **184** in response to five different A-V delays that were tested, with line segments drawn between the data points. In one embodiment of operation, slope calculation module **188** determines the slopes associated with each P-MVC line segment between corresponding adjacent tested A-V delay values, and

stores an indication of such slopes in memory **186**. Based on these slopes, A-V delay selection module **190** selects an A-V delay that is deemed appropriate for use in subsequent delivery of ventricular stimulations in conjunction with intrinsic or paced atrial depolarizations. In a very general sense, the shorter pairs of A-V delays typically manifest larger associated slopes than the longer pairs of A-V delays, at least when the extremes of the graph of Figure **3** are inspected. In one embodiment, the appropriate A-V delay is selected by beginning at the shortest pair of adjacent A-V delay values, and working toward the longest pair of adjacent A-V delay values. The appropriate A-V delay is selected as the shortest of the A-V delay pairs with which an adjacent shorter one of the A-V delay pairs provides a larger slope than an adjacent longer one of the A-V delay pairs. This is illustrated in Figure **3** by the selection of the second shortest A-V delay as the appropriate A-V delay for the timing of subsequent atrial and ventricular senses and/or stimulations, because, proceeding from shorter A-V delays to longer A-V delays, the second line segment manifests a smaller slope than the adjacent first line segment.

In another embodiment, the "knee" in the hockey stick shaped curve of Figure **3** is obtained by extrapolating a line based on the shortest A-V delays, and a second line based on the longest A-V delays, determining the intersection of these two lines, and determining the associated A-V delay corresponding to the intersection. This technique, which does not require slope calculations, is illustrated generally by Figure **4**.

Figure **5** is a flow chart illustrating generally one embodiment of an example technique for selecting an appropriate A-V delay at which to deliver subsequent ventricular stimulation therapy. At step **500**, an test A-V delay is initialized, such as for example, to the lowest A-V delay value in a range of test A-V delay values. At step **505**, a ventricular stimulation is delivered after an intrinsic or paced atrial depolarization, separated therefrom by a time equal to the test A-V delay. At step **510**, a heart acceleration is sensed. At step **512**, the baseline dc or low frequency component of the detected heart acceleration signal is removed by highpass filtering.

At step **515**, the heart acceleration signal is lowpass filtered. At step **520**, the lowpass filtered heart acceleration signal is differentiated to obtain a resulting first derivative heart acceleration signal. At step **525**, a first peak of the first derivative heart acceleration signal (i.e., in this case, a first negative peak occurring after the ventricular stimulation and before a next sensed or paced atrial depolarization) is detected and deemed a fiducial point associated with mitral valve closure for that cardiac cycle. At step **530**, a P-MVC time interval is measured between the paced or intrinsic atrial depolarization and the corresponding subsequent MVC fiducial point during the same cardiac cycle. At step **535**, if the test AV delay is not at the end of the range of test A-V delay values, the test A-V delay is incremented at step **540** and steps **505** through **535** are repeated. If, however, at step **535**, the test A-V delay is at the end of the range of test A-V delay values, then at step **545** an appropriate A-V delay for subsequent delivery of ventricular stimulations is selected, such as by using the techniques described with respect to Figures **3** or **4**.

Although the system and its operation have been particularly described above with respect to selecting an A-V delay for the delivery of right ventricular stimulations (for patients who respond to such therapy), it is understood that the system and its operation is even more applicable to selecting an A-V delay for the delivery of left ventricular stimulations or biventricular stimulations (for patients who respond to such therapy), as illustrated in the schematic/block diagram of Figure **6**. Moreover, the test values of A-V delay and/or the selected A-V delay value may be measured from either right or left atrial depolarizations (paced or sensed). In fact, the data illustrated in Figures **3** and **4** is illustrative of data actually obtained using A-V delays taken with respect to the left ventricle.

In Figure **6**, system **100** further includes a lead **700** having at least one electrode associated with left ventricle **115D**, intravascularly, epicardially, or otherwise. In this example, lead **700** is introduced into association with left ventricle **115D** by inserting lead **700** through right atrium **115A** and into coronary sinus **702** and/or one of its tributaries such as the great cardiac vein. In this manner,

an electrode, such as an approximately basal electrode **704** or a more apical electrode **706** is placed in association with a portion of left ventricle **115D** for sensing or pacing left ventricular heart contractions. This arrangement also allows delivery of simultaneous or offset biventricular stimulations for coordinating the relative timing contractions of right and left ventricular heart contractions. It further allows the delivery of simultaneous or offset left ventricular stimulations for resynchronizing the spatial nature of the left ventricular depolarization by providing simultaneous or offset stimulations at more than one left ventricular electrode, such as at each of electrodes **704** and **706**. The configuration illustrated in Figure **6** may be used in conjunction with the above-discussed techniques for selecting the appropriate AV-delay, thereby establishing the AV delay value as measured from an atrium to one of electrodes **704** and **706**. Such a configuration is particularly useful for, among other things, patients having left bundle branch block (LBBB).

It is to be understood that the above description is intended to be illustrative, and not restrictive. For example, the above-described embodiments may be used in combination with each other. Many other embodiments will be apparent to those of skill in the art upon reviewing the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. In the appended claims, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein."